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VALUE ADDED ANALYSIS FOR ARMY EQUIPMENT MODERNIZATION

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ABSTRACT

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1. INTRODUCTION

Each year the US Army considers numerous proposed programs to procure new weapon systems and other equipment. These proposals all have proponents who assert that their systems satisfy Army needs and improve significantly upon predecessor systems. These assertions are backed with analyses conducted by the command that is responsible for the specific mission areas that are to be improved, and the total cost of all proposals would be billions of dollars annually. However, Army procurement budgets have been reduced by half since the 1980's and are not sufficient to fund all the systems and proposals. Funding pressures will continue to intensify as the perception of threats around the world changes and the federal budget deficit continues to loom over all public spending. As a result, solid and impartial analysis is needed at the Department of the Army level to provide insightful recommendations on which systems to fund.

This paper describes a modeling methodology called *Value Added Analysis* (VAA), which helps the US Army meet this critical analysis need. The *Value Added* means incremental return on a system's investment based on its contribution to the Army's effectiveness in performing its missions. VAA uses a family of simulation, statistical, and decision analytic models to estimate the value added and cost of alternative procurement programs. Optimization techniques are then applied to identify a theoretically optimal mix of weapon systems and equipment. The "optimal" solution is then used as a foundation for parametric analyses that provide senior leaders insight into the implications of system trade-offs and changes in planning guidance.

Prior to VAA, the process that evolved over many years of procurement budgeting was to convene a separate panel to evaluate and prioritize alternative weapon systems and other equipment for each functional area of the Army (fire support, maneuver, aviation, etc.). These panels acted independently, and the process did not include adequate means of integrating the separate panels' recommendations into a balanced Army program. VAA overcomes this shortcoming of the traditional approach by evaluating the value added of all the alternative systems in a consistent and objective manner, allowing optimization of the procurement program.

Every other year, the Army produces its funding plan called the Program Objective Memorandum (POM). VAA has been used since 1991 to support the decisions made by the Office of the Deputy Chief of Staff for Operations and Plans and the Programs Analysis and Evaluation Directorate, which have the primary staff responsibility for preparing the POM and making recommendations to senior leaders.

The remainder of the paper describes VAA's overall framework and the evolution of the process over the past half decade.

2. OVERVIEW OF THE VAA ANALYTICAL FRAMEWORK

The VAA analytical framework provides a road map for conducting Army procurement program tradeoff and capital budgeting analyses. It's structure is similar in nature to other efforts of this type. For example, Hall, et. al. [7] describe a similar modeling framework that was used to assist in program funding decision making at the National Institutes of Health. Peereboom, et. al. [18] used related techniques to select a portfolio of environmental programs for the U.S. Department of Energy. Another approach for the solution of the Army capital budgeting problem for procurement programs has been suggested by Anderson [1]. His methodology departs from the one described here in that it considers a broader variety of procurement programs, but it does so in a less detailed fashion.

Figure 1 depicts the six modules in the VAA analytical framework. This framework could be used for any of the appropriations (operations and maintenance; military construction; research, development, and acquisition (RDA); etc.). The scope of the study effort has historically been limited to selected major weapon systems. These are the weapon systems that are important in the Army Modernization Plan and funded using RDA appropriations. This scope captures over fifty percent of the dollar value of the RDA appropriation, addresses the "big issues", and focuses analyses into key decision areas.

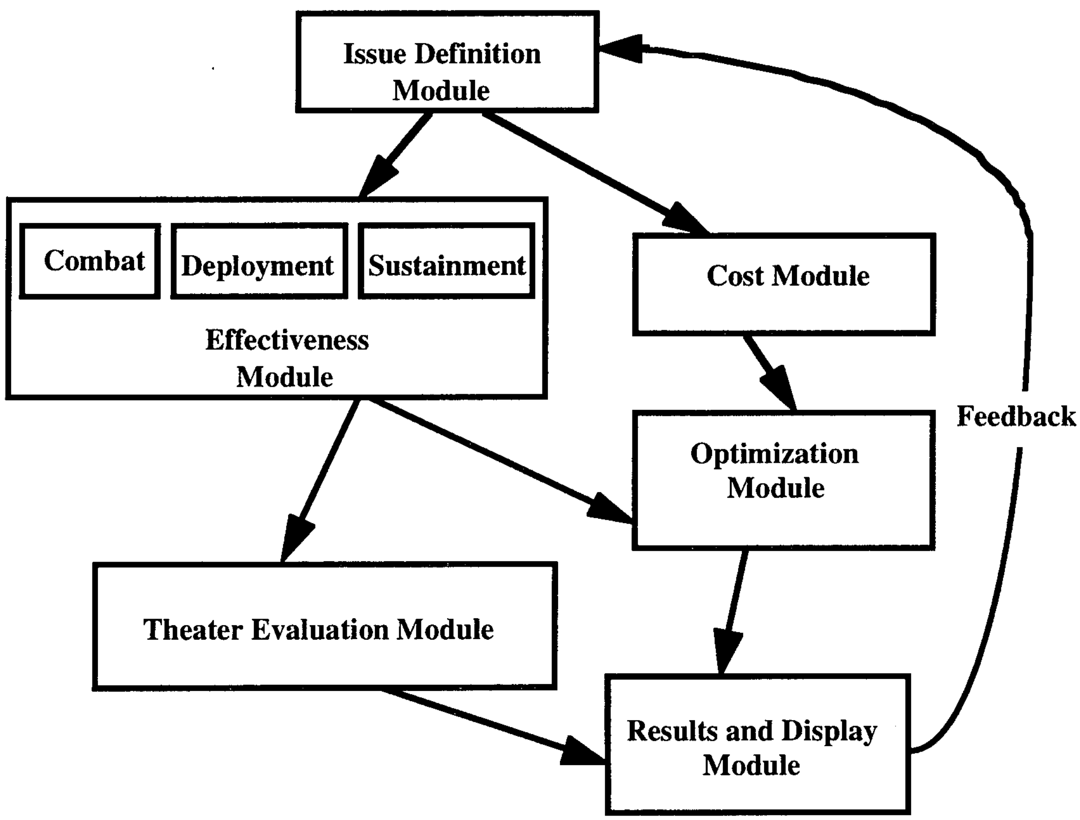

Figure 1. Value Added Analysis Methodology Overview

The VAA methodology's six modules correspond to a loosely coupled process consisting of the following steps: (1) Definition of the context of the problem and identification of important issues to be studied; (2) Determination of the benefit of procuring the systems based on their contribution to the combat effectiveness of the force, the deployability of the force, and the sustainability of the force; (3) Estimation of the of the life cycle costs for each alternative program; (4) Analysis of the cost-benefit of the systems by means of a mathematical program; (5) Evaluation of the recommended system mix in various theaters of operation; and (6) Presentation of the results to the decision makers.

Each of the steps in the VAA framework is essentially a separate analysis, the output of which provides input to a subsequent module and analytic insights that are of value to individual elements of the Army Staff. Each of the modules will be addressed in the sections that follow.

3. ISSUE DEFINITION

The Issue Definition Module has two purposes. The first is to establish a broad context for the study in terms of time frames and scenarios to be analyzed, the list of major item systems to be considered, the criteria by which system contribution should be judged, and the measures of effectiveness (MOE) to be used. These factors define how the benefit of the candidate systems is to be articulated numerically. As such, issue definition will have tremendous, often subtle impact on the perceived value of a potential weapon system. Therefore, it is essential that decision makers understand the implication and importance of this stage in the process. The second purpose involves identifying the very specific "What-If" questions that arise in the POM building process. Both of these aspects are discussed in this section.

3.1 Study Context

The VAA study considers a 15 year time horizon corresponding to the years considered in Army acquisition planning. This time horizon is considered in two parts. The first five years are called the POM years, and the following ten years are known as the extended planning period (EPP). Over that time, new systems will be introduced into the force and changes will occur in the enemy threat. As a result, the expected contribution of the systems under consideration by the VAA process will fluctuate. Ideally we would like to predict the performance of the force and the relative contribution candidate systems in every year of the time horizon, in every conceivable scenario. Even if it were possible to articulate all possible scenarios, the cost in time and dollars to model every scenario explicitly in this manner would be prohibitive.

A natural way of choosing the years to perform the evaluation is based on the two parts of the planning horizon. Assuming a two year lag between procurement and fielding of new systems, all systems procured in the POM period would be available on the battlefield by the seventh year of the time horizon. Similarly, all the systems procured through the EPP would be available for combat two years after the time horizon. Therefore, the evaluation is performed and the candidate systems are simulated explicitly using an appropriate enemy threat force for two years after the POM period and two years after the EPP. The values of relevant MOE for intermediate years are estimated using linear interpolation.

The Defense Planning Guidance, issued by the Secretary of Defense, identifies scenarios that provide the foundation for the Army's modeling and analysis. In VAA two combat oriented scenarios are currently modeled, each in two time frames. Future iterations of Value Added Analysis could consider other, more frequently encountered situations such as low intensity conflict and humanitarian relief missions. Nothing inherent in the methodology precludes these scenarios from being included, given that sufficient resources and time are available to estimate the expected contribution of the candidate programs in these situations.

The specific list of procurement programs to be considered has been historically based on the following considerations. First, the study sponsors were primarily interested in high cost combat systems. These systems spanned the entire range of combat functions and included new and upgraded combat vehicles, artillery, helicopters, intelligence systems, logistics systems, and command and control systems. Second, some procurement decision was likely to be needed regarding each program in the analysis. If it was generally agreed that the decision to fund or not fund a particular program had already been made, the program was not included on the list. Programs with already approved funding were included in the base case, and were modeled in every simulation run. Finally, a credible job of modeling each system was required. Some of the new concepts in command and control, for example, were omitted from the list due to our inability to model them. Ultimately, a list of about 50 programs were selected to be analyzed.

The selection of the specific criteria and measures of effectiveness used to quantify a system's level of performance will be discussed in subsequent sections.

3.2 Specific Issues for Analysis

The second part of the issue definition module involves detailed questions. These might be specific questions regarding individual weapon systems, groups of systems, perturbations to available funding, or changes in other model parameters. The intent of these questions is to develop insight into the tradeoffs between different mixes of the systems that might be procured or to assess the impact of changes in planning constraints. Normally, these issues are identified as excursions to the primary analysis effort.

Historically, the questions were specific and based on results of previously presented analyses. Examples of these "What-If" questions are: If this maneuver system that was not recommended for procurement is included in the program, what programs should then not be funded?; or, How would the recommendation be changed if the available funds were reduced by $500 million per year in 1998-2000?

Our experience has also been that almost every excursion produces a series of subsequent questions which establish a feedback loop in the analysis. This interactive process was normally accomplished within 24-48 hours to stay inside of the decision cycle that accompanies critical stages of the planning process.

4. COMBAT EFFECTIVENESS

The Army invests in new weapon systems and logistical support systems to improve the effectiveness of our forces in combat. All of the proposed programs are either improvements

over an existing system or they are new systems that are designed to meet a validated requirement on the battlefield. The requirements represent a heterogeneous set of contributions, many of which contribute indirectly to the battle. VAA uses experiments conducted using combat simulation modeling to estimate homogeneously the relative contribution of proposed systems. The following provides a description of this estimation process.

4.1 Combat Simulation Modeling

For a combat simulation output to be useful, the model used must represent the candidate systems at an appropriate level of resolution. For this application of Value Added Analysis, a corps-level combat model was used. The use of this level of resolution was important for several reasons. First, US Army planning typically calls for the deployment of corps or corps-like structures to the areas of the world and the potential conflicts being used as the basis for the combat modeling. Second, a corps-sized force makes use of a fuller mixture of maneuver, fire support, combat environment, logistics, and command and control (C2) than lower (e.g., division) level organizations. Finally, corps-level simulations have the sensitivity necessary to evaluate weapon systems and their effect in a level of detail that would be missing in a more aggregated model. The Corps Battle Analyzer (CORBAN) [24] was chosen to simulate the overall battle.

CORBAN is a time-stepped, closed-loop, deterministic simulation that models combat at the corps/army level. It can simulate battles ranging in size from one battalion versus another, to a battle of eight US corps opposing eight "Red" armies. Resolution of the model is at the battalion level. However, individual weapon systems and their characteristics are modeled. Maneuver and fire support systems can be modeled directly in CORBAN. However, the air defense and logistics systems required the use of functional area models and other off-line analysis to provide calibration input to CORBAN so that the effects of these systems could be captured.

A base case is established for each scenario/time frame using forces equipped with systems that are known to be available during the particular year of interest. Excursions are then developed by replacing base case systems with new weapon systems, or adding new systems, to produce new results that are compared with the base case results. The results of these excursions are used to determine the contribution of each candidate system to the effectiveness of the force.

4.2 Combat Measures of Effectiveness

The choice of combat measures of effectiveness (MOE) is always a difficult one. An advantage of the VAA methodology is that it is not limited to only one MOE. Therefore, a set of MOE can be selected that are deemed important by the study sponsors. Ideally that set of MOE will characterize the performance of the force as a whole and be sensitive to the contributions of the candidate systems under consideration.

During prototype implementation of the VAA methodology, data on several MOE were collected. These included loss exchange ratio (LER), which is the ratio of red major weapon systems lost to that of blue; correlation of forces and means (COFM), a measure of red force strength in an attack corridor with respect to the blue combat strength in the same corridor; blue

force surviving (BFS) and fractional exchange ratio (FER), which are defined below; and red force movement (RFM), a measure of the distance moved by the red force computed using its center of mass. Of these, all but BFS were significantly correlated, indicating that some relation exists between them. Since we would like as much independence between the MOE as possible, we chose only one measure among the correlated MOE to include in the analysis.

Fractional exchange ratio was chosen as a method for determining the lethality of the force, measuring the proportion of red losses compared to the proportion of blue losses. FER is a commonly used measure in the analysis of weapon systems and is familiar to the receivers of the analysis. Also, using historical combat data, Helmbold [8] showed that FER is a good indicator of success in battle.

FER is computed as follows. Let I_B be the index set of blue systems included in the calculation. This set of systems is limited to combat vehicles, self-propelled artillery, and aviation systems. These systems account for most of the combat power of the force. Let I_R be the index set of the corresponding red systems. With Ψ_f being FER we have

$$\Psi_f = \frac{\sum_{i \in I_R} r_i \Big/ \sum_{i \in I_R} R_i}{\sum_{i \in I_B} b_i \Big/ \sum_{i \in I_B} B_i},$$

where b_i = quantity of blue system i lost during the simulated battle,

B_i = quantity of blue system i available at the start of the simulation,

r_i = quantity of red system i lost during the simulated battle, and

R_i = quantity of red system i available at the start of the simulation.

Despite its stated advantages, the mathematical form of FER, namely a ratio of ratios, is a potential source of inconsistency. Care must be taken to control unwanted variation between simulation runs. A great deal of detailed output analysis was required to ensure consistency between the runs. In particular, the establishment of a suitable stopping criterion was found to be important in controlling irrelevant variation.

Where FER is a measure of success in battle, BFS is a measure of the combat power remaining after the battle, available for a subsequent conflict. As such, BFS represents a measure of the expenditure of resources needed to accomplish some mission.

BFS is computed as follows. Using the above notation, and with Ψ_b being BFS we have

$$\Psi_b = \frac{\sum_{i \in I} \xi_i (B_i - b_i)}{B_i},$$

where I = set of all blue systems, and ξ_i = combat capability weight of system i.

Note that the ξ_i parameters are data used in the CORBAN decision process. These parameters are used to reflect the fact that different items of equipment used by combat units

have different levels of importance. A great deal of controversy exists in the combat modeling community regarding the use of these static measures, and ideally we would avoid their use. Nevertheless, some accommodation must be made to the consideration of the relative importance of the various pieces of equipment used by combat forces, and weighting is a commonly used technique to accomplish this consideration.

To overcome this problem, and to better capture the values of the decision makers, BFS was replaced by blue personnel casualties (BPC), denoted as Ψ_p, as a measure of the human cost in accomplishing the mission of the force. This is a straight forward measure that is not a ratio and does not require additional weighting. In addition, it reflects a national defense goal of winning conflicts quickly with few personnel lost.

Clearly, FER and BFS or BPC are not independent. Arguably no two combat MOE are totally independent, and no single MOE is sufficient to provide enough information for a complete analysis. These MOE were understood and accepted by decision makers and appeared to highlight important performance differences between systems that were under consideration.

4.3 Response Surface Model

The MOE described above are proxy measures of the performance of an entire combat force in battle. To estimate the benefit of candidate procurement programs, we must identify that system's contribution to the effectiveness of the force with respect to the proxy measures. The most common, and simplest, method of determining this contribution is to establish a base case and then to add each new weapon system one at a time, measuring the changes that occur with respect to the particular MOE. These changes in the MOE from the base case are then taken to be the quantity a weapon system contributes to the outcome of the battle. This method ignores the fact that different combinations of combat systems result in different combat outcomes and that, presumably, several of the candidate procurement programs would be funded. Thus, some measurement must be taken that considers, at least in some aggregate way, the presence of other new systems on the battlefield.

The ideal solution would be to simulate all possible combinations of candidate systems. While this method is practical for situations with a small number of candidate systems, the number of combinations grows quickly. For example, if one had to explore every combination of 40 different systems, the number of potential runs would be 2^{40}, or 109.9 billion simulation runs.

A compromise between these two extreme methods is to apply a statistical methodology. VAA's model is based on a general linear model (GLM) formulation using a Plackett-Burman design. See Plackett and Burman [19]. It was developed to perform two functions. First, the methodology defines a design matrix which specifies the combinations of candidate systems that are to be simulated in each run of the combat model. This design plan efficiently maps the sample space so that the second function, the building of a regression formula that can be used to predict the response of the CORBAN model with respect to the MOE, can be performed.

Plackett-Burman's design methodology specifies the construction of the design matrix, U. This matrix represents a map of all the independent variables' values for each computer run. Each row corresponds to a specific computer run and each column corresponds to a different factor. In the case of VAA, the systems being considered for procurement are the factors. The values of the

matrix elements, u_i, are either 1 or 0 which represent the presence or absence of the system in the simulated battle, respectively. See Mann and Loerch [15] for a complete description of this model.

The general linear model is of the form:

$$\Psi_j = \beta_0 + \beta_1 u_1 + \beta_2 u_2 + \beta_3 u_3 + \ldots + \beta_m u_m, \; j = f, b, p,$$

or in matrix form,

$$\Psi_j = U\beta,$$

where Ψ_j is an output vector for MOE j of the model run results, β_0 is the effect of the base case weapons, β_1 through β_m are the effects of systems 1 through m in the excursions, and U is the design matrix of binary independent variables whose construction is described below. The values of β_1 through β_m are measures of the average contribution of candidate systems 1 through m to the effectiveness of the force, and can be estimated using the standard formula for the GLM. See Neter, et. al. [17]. This model isolates only the presence of main effects without considering any interaction effects.

To account for interactions, careful post-analysis of the simulation output is required so that combinations of systems that perform particularly well, or poorly, are identified. Additional simulation runs are added to the original design so that extra degrees of freedom are available to analyze specific interactions. Systems that are determined to perform in a synergistic fashion are reported to the sponsors and are subsequently considered together. Conversely, systems that interfere with each other can be forced to be procured separately. These relationships between systems can be easily handled in the optimization module.

Note that in each excursion a different combination of candidate weapon systems is portrayed. Care was required to ensure that the proper doctrine, tactics, and methods of employment of these weapon systems, both singly and in combination, were represented. This requirement greatly increased the workload as well as the time needed to complete the combat modeling for the study.

5. EVALUATION OF OTHER FACTORS

A shortcoming of previous attempts to develop a program tradeoff methodology was that these methodologies concentrated on combat measures of effectiveness almost exclusively. These preceding methodologies (see, for example, Shedlowski [21]) did not accommodate any of the additional factors which decision makers felt were important in making tradeoffs between competing weapon systems. In this section we discuss the inclusion of these factors in VAA.

5.1 Early Work

The identification and definition of the other factors that are important in evaluating how much a system contributes to the effectiveness of the force are performed as part of Issue Definition. The decision as to which factors should be included has been a source of controversy in the past. In the early applications of VAA, attempts were made to include a broad range of factors whose importance was readily acknowledged. Some of the factors considered included:

(1) Political Risk. This criterion is used to evaluate the level of support for the program across the political spectrum.

(2) Operational and Technical Risk. This measure represents a subjective evaluation of the probability associated with a program meeting all of its stated performance criteria.

(3) Impact on Sustainability (Combat). This criterion is aimed at the burden each system places on the logistical system.

(4) Programmatics. This factor measures the complexity and difficulty of contracting for and manufacturing the systems

(5) Asset Versatility and Deployability. This criterion measures the usefulness of the system in different theaters of operations and different combat environments, as well as the ease of deploying a force equipped with the candidate systems.

(6) Criticality of Need As Related to Current Capability. This factor attempts to identify systems that meet some critical need, or overcome some important shortcoming in force capability.

These criteria were viewed to be entirely subjective and measurement was performed by using a survey of subject matter experts from the Army Staff. The original plan called for the use of the Analytical Hierarchy Process (AHP). AHP generates measures based on pairwise comparisons between the candidate systems with respect to each criterion. See Saaty [20]. However, since almost 6000 comparisons would have been needed for this analysis, this survey technique was abandoned. In its place, an individual rating was made for each system on each criterion using the 1 - 9 scale from AHP, higher being better. The survey reflected a consensus among program managers, responsible staff officers at Army Headquarters, and other organizations as appropriate.

The ratings obtained in this survey were then used as part of the overall effectiveness scores for the candidate systems for use in the objective function of an optimization. The method used to generate the overall effectiveness scores is discussed in the next section.

This approach encountered difficulties. First, two of the identified criteria were risk related, representing an expert's assessment of the probability that the system would be fielded and that it would be available to the combat commander when it was required. In theory, a system that was technically infeasible and politically impossible to support but performed very well in the combat simulation could be preferred over a very realistic alternative that scored slightly less well in the combat simulation. Second, if one assumes that the combat simulations are reliably reflecting the performance of systems on the battlefield, and the combat MOE are reflecting the values of our combat leaders, then one could reasonably assume that the simulation is capturing "criticality" of the need. Third, the majority of the "programmatics" issues were being captured in the cost module and the constraint matrix of the optimization.

5.2 Subsequent Efforts

Based on this early experience the decision was made to eliminate several of the evaluation criteria, as well as the subject matter expert survey. Although the modeling effort was thought provoking and produced some good insights and discussion, not much contribution was made to the development of a quantitative measure of the systems' benefit to the force.

Consequently, the list of other factors considered explicitly was paired down to two measurable attributes, contribution to sustainability and contribution to deployability.

5.3 Sustainability Analysis

The Dictionary of US Army Terms defines sustainability as the capability of the force to maintain the required level of intensity and duration of combat activity to achieve the force objectives over time. Loosely translated this means that the force is well sustained when the commander has sufficient resources to do what he wants to do. The decision logic of the CORBAN model includes the ability to track the usage of key logistical resources for each unit represented on its simulated battlefield. Thresholds are established for levels of supplies, below which the unit cannot attack, must withdraw when confronted, etc. This facility of the model was used to estimate the contribution of the candidate systems to the sustainability of the force.

Discussions were held with expert logistical staff officers to determine which commodities should be included in the analysis. Fuel and ammunition supplies were acknowledged to be the most restrictive battlefield resources. Therefore, they were selected as the MOE for sustainability.

The measure of sustainability was computed as follows. Let t_{pq} be the total time combat unit p was below the threshold level of commodity q during the simulated battle, and T_p is the total time unit p was viable during the battle. Then, if P is the set all combat units, the sustainability of the force with respect to commodity q is written as

$$S_q = 1 - \frac{\sum_{p \in P} t_{pq}}{\sum_{p \in P} T_p}.$$

This quantity is collected for each simulation run and the contribution of each system is determined using the same response surface methodology that was used to evaluate contribution to combat effectiveness.

A limitation of this method is that the simulated scenario never exceeds seven days and is typically only three or four days in duration. As a result, the force is not badly stressed in terms of sustainment in that time and making strong statements about contribution of individual systems is difficult. Nevertheless, the observation that the force is well sustained in the early parts of the battle is an important one. We also observed that systems that produced enemy attrition in the deep battle, such as some missile systems with long ranges, contributed strongly to sustainment because their effective employment reduced the intensity of the close battle. As a result, less fuel and ammunition were expended.

5.4 Deployability Analysis

Where other measures of effectiveness and contribution could be estimated using the combat simulation, the effect of fielding the candidate systems on the ability to deploy the force

from a location in the continental United States to an overseas location could not. As a result, this part of the analysis was completed by experts from the US Army's Military Traffic Management Command (MTMC).

Three characteristics of the candidate systems were used to estimate their relative impact on the deployability of the force: weight in short tons, surface area in square feet, and volume in cubic feet. These measures included not only the end item, but all associated items of equipment. This is often referred to as a "unit set". Additionally, information on scenario and force structure, including equipment densities, were input to various deployment and mobility models that are used by MTMC to estimate resource requirements for force deployments. Estimates of impact are made by comparing the required resources with those of the system that the candidate system replaced.

This procedure was performed for each of the three phases of the movement, the so-called "fort-to-port" phase, the strategic or inter-theater phase, and the intra-theater or "port-to-foxhole" phase. Resources that were considered included quantities and types of railcars and other surface transportation assets like flatbed trailers and heavy equipment transporters. Of particular interest was whether or not the equipment that was to be transported by air required the use of the larger, but less numerous, C5A cargo aircraft. Since C5A's are a very scarce and important strategic mobility resource, the requirement of their use for a new item, when its predecessor system could be transported using the more abundant C141 aircraft, would represent a significant negative impact on the deployability of the force.

A measure of contribution to the deployability of the force for each leg or phase was developed by making the evaluation described above, weighting the assets required based on existing and forecast availability and capability, and then summing the scaled and weighted scores for each system. An overall measure was then computed by summing the weighted scores for all legs of the deployment. These weights are also based on the capabilities that exist to execute the movement phases.

6. EFFECTIVENESS INTEGRATION

The purpose of the effectiveness integration module is to derive a set of system "scores" that reflects the relative contribution of the potential weapon systems, or acquisition programs, to the performance of the Army in combat. The scores are used to form the coefficients in the objective function of the optimization module. The reliability of any acquisition strategy that is recommended by the mathematical function relies on the quality of these coefficients. These coefficients, then, must be developed in a rational and consistent way to be meaningful. In particular, the individual measures or attributes that make up the overall scores and the weights on the importance of these attributes, must reflect the values of the Army leadership and must be consistent with Army objectives.

6.1 Early Work

Initial efforts to integrate the heterogeneous measures of effectiveness into a homogeneous measure applied the Analytic Hierarchy Process (AHP) [20] to produce the

criteria weights and a multi-attribute decision algorithm called the Technique for Ordered Preference by Similarity to an Ideal Solution (TOPSIS) [9, 25] to compute the overall system scores. Research into the behavior of the algorithms as they were applied to this problem indicated that spurious results could occur. See Maxwell and Buede [16]. Moreover, research into the algorithms in general indicated that the results being experienced in the VAA application were symptomatic of more general shortcomings. These are discussed by Buede and Maxwell [2], Dyer [5], and Kloeber [11]. Because of these difficulties the approach evolved into the model described below.

6.3 The Current Model

There are two key elements to any model that must be separated and addressed explicitly, if a model is to provide meaningful insight. These are issues of fact and issues of value. For further discussion of this separation see Keeney [10]. Sections Four and Five previously identified and discussed five criteria that are being used as proxies for contribution of a weapon system to the overall performance of the Army. Section Two identified two time frames and two scenarios that are to be considered in developing the relative contribution of systems. These data provide the "factual" information that will be used to derive the coefficients. For example, adding system X to the force mix increases the expected FER by .5, from 1.0 to 1.5 in the far term contingency scenario. Similarly, the substitution of system Y for an old system reduces the lift requirement for the modeled force by approximately 70 C-141 sorties, or approximately one percent.

The factual outcomes described above will either be true, or not, or we may never know because the situation does not occur. How senior leaders feel about improvements within, and trade-offs among these measures are issues of value. There is no "right" or "wrong" answer, and these are the judgments for which these leaders are responsible. Analysis must seek to identify and apply, as accurately as possible, the values of the Army's senior leaders. Where possible consensus should be sought. Where consensus is not possible, robust sensitivity analysis should seek out the implications of the value differences with respect to the alternatives under consideration. VAA addresses this goal directly.

In the most current iteration of the analysis, the MOE were arranged hierarchically as indicated in Figure 2. The figure points out the fact that the overall "score" for a system in a given time frame is a function of the previously identified measures. This model then provides a context within which to assess the preferences of senior leaders. In this instance of the analysis approximately ten general officers and senior civilians were interviewed.

The actual interview with the senior leaders was a structured interview using a derivative of an elicitation technique called Simple Multi-attribute Rating Technique (SMART) developed by Edwards [6]. This method employs an approximation technique that has been successfully applied in practice by VAA team members. It was chosen for three reasons. First, it has proven to give reasonable weight approximations for multi-attribute problems with considerably smaller labor investments than more rigorous techniques. Second, since senior leader time is a valuable commodity, analysts needed to be in, understood by the decision maker, elicit their input, and out of the office in under an hour.

Finally, the elicitation session needed to be highly interactive and allow for immediate feedback to the decision maker. This interaction assured that the decision maker and analyst were communicating clearly and served to build senior leader confidence in the analysis process by "getting their hands dirty". Commercially available software made this interaction possible.

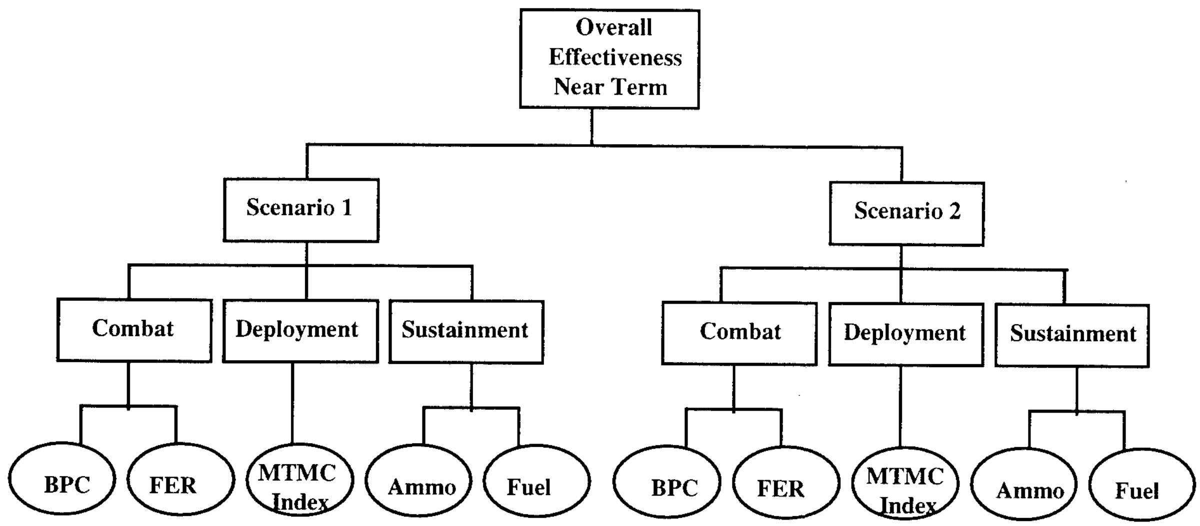

Figure 2. Value Added Analysis Hierarchy

In order to complete an interview using SMART an analyst must clearly identify the attributes, as well as the range those attributes vary over in the given decision context. This specificity appropriately frames the judgments for the decision maker and allows for better informed trade-off or ranking decisions than other methods. This change resulted in a much greater degree of consensus among decision makers regarding the relative importance of attributes than previously employed multi-attribute methods.

6.4 Integration Module Outputs

As previously identified, the most important output of the Integration Module is a set of system coefficients. The coefficients are not, however, the same value that is produced by the multi-attribute function. It is derived from that value based on two relevant factors. First, the contribution to the force that is estimated by the simulation and experts considers the system as part of a contingency corps. The potential systems are assigned to appropriate units in varying quantities based on appropriate doctrine and mission objectives. These quantities must be adjusted so they are consistent with incrementing units being considered by the mathematical program. Additionally, the objective function requires a ratio measure. This is derived by estimating the performance of the baseline force. This baseline is then subtracted from the estimated performance of the force with the system. The difference is the marginal, or incremental, improvement of the force's performance.

7. COST ANALYSIS

The purpose of the cost analysis module is twofold. First, accurate system procurement costs must be estimated, including research, development, test, and evaluation (RDT&E) costs; fixed production costs; and variable production costs. These costs are necessary for conducting the optimization which finds the mix of systems that maximizes the effectiveness of the force subject to constraints on the Research, Development, and Acquisition (RDA) budget. Second, given optimized quantities of procured systems, estimates must be computed of the other aspects of the life cycle costs of the system. These aspects include fielding costs, sustainment costs, and facilities costs. Once the various components of the life cycle costs are computed, they must be made available in an easily accessible form so that information regarding the costs of the candidate systems can be analyzed.

An important aspect of estimating the procurement costs associated with the candidate systems is determining whether or not a significant relationship exists between the unit cost of a system and the quantity procured. For many of the candidate systems, particularly the developmental systems that involve new technology, this cost-quantity relation is significant and nonlinear. As such, this relationship must be considered and accounted for to ensure accurate results. For the purposes of this study, the cost-quantity relationship reflects economies of scale in terms of materials and labor, as well as "learning" on the part of the production labor force.

Although there are many mathematical models of these so-called learning curve costs (see Dutton, et. al. [4] for a review of about 300 articles that discuss learning curves), the so-called "power" or "exponential" model was chosen to describe the cost-quantity relationships in the VAA study. This model is commonly used in defense and industrial cost estimation and was adopted in VAA to maintain consistency between cost estimates used in this study effort and others provided for the purpose of staff planning and budgeting. The model has the following form:

$$c = Ay^{-b},$$

where

c = cost of the y^{th} unit of a system produced,
A = the notional cost of the first unit produced,
b = cost-quantity slope coefficient,
y = accumulated number of items produced.

Notice that this function is nonlinear as is the case in almost all representations of learning effects.

Average unit procurement costs are used for the systems that exhibit no appreciable learning behavior. Fixed costs, i.e., costs that do not depend on the quantity of an item procured, are also included. These costs include RDT&E expenditures and fixed production costs. Cost data was obtained from multiple sources including the various program managers that are responsible for the candidate procurement programs.

Following the computation of a recommended system mix for procurement, together with optimal procurement quantities, the life cycle costs for the programs are estimated using the Life

Cycle Cost Model (LCCM). This model, implemented on a spreadsheet, uses standardized cost definitions (see DCA-P-92 (R) [22]) and previously determined cost estimating relationships to compute the cost of fielding, sustaining , and providing adequate facilities for the system. The LCCM automates the recosting of the life cycle costs based on a new set of quantities, thus providing a tool for conducting cost related "What If's".

8. OPTIMIZATION

The actual cost effectiveness analysis contained within the Value Added Methodology is performed in the optimization module. In the current version of VAA, the final determination of a recommended acquisition strategy is based on the acquisition cost of a system, the combined effectiveness value which includes both the combat and other factor values, the force structure requirement for the systems to fill the force, the capability of industry to produce the systems, and budgetary ceilings. Furthermore, since the current budgetary environment has resulted in more programs being available for procurement than there are funds available to pay for them, it was clear that some method of identifying systems that should be left unfunded was needed. Also, some programs because of their operational requirements, needed to be linked together in such a way that the model would only recommend that operationally logical sets be procured. The VAA optimization model was developed as a mixed integer program capable of handling the factors discussed above.

The objective of the model is to suggest a mix of systems for procurement that will be as effective as possible in combat, subject to a total budget authority ceiling. The values developed in the effectiveness integration module are used to create a single measure of a system's worth for each year in the planning horizon, reflecting all the measures of effectiveness for each program, weighted by the senior leader survey process, and scaled to a per item value. The objective of the mathematical program is to maximize the sum of these system values. This is done by constraining the model to an overall Total Obligation Authority (TOA) which represents a yearly budget ceiling, a particular Army force structure which determines the quantities of the new systems required, and the ability of the industrial base to produce the systems as defined by start and stop dates and annual production quantities. Each of these constraints is computed by year for both the POM years and the EPP, a total of fifteen years. The formulation of the model can be summarized as follows.

Maximize: Force effectiveness,
Subject to: Budget ceiling,
Production limitations,
Force structure requirements, and
Decision constraints,

where the decision variables for this model are the quantities of each system procured in each year.

As mentioned, available funds are never sufficient to procure all candidate systems, even at the lowest allowable quantities. Also, quantities must be constrained such that, if a program is recommended, the requisite quantities will be procured to meet force structure requirements and to not exceed the capabilities of the existing or planned production facilities. Thus a mixed integer programming formulation is introduced where the variable u_i is defined as follows:

$$u_i = \begin{cases} 1, & \text{if candidate system i is recommended for procurement,} \\ 0, & \text{otherwise.} \end{cases}$$

So the constraints on the quantities produced take the following form:

$$P_{min_{ij}} u_i \le x_{ij} \le P_{max_{ij}} u_i,$$

where

$$x_{ij} = \text{ the quantity of system i procured in year j,}$$

and $P_{min_{ij}}$ and $P_{max_{ij}}$ constrain the yearly production quantity. Note here that if the system is not recommended for procurement, the value of u_i is zero and the quantities will also be constrained to be zero. Similar constraints are implemented on the total procurement of each system. The binary variable u_i is also used to assess fixed costs in the budget constraint.

Use of the binary variables, u_i, is made to constrain the model to implement previously made decisions. These decisions are implemented in the model by constraining linear functions of the vector of u_i variables, $f_k(\mathbf{u})$. For example, if the decision is made to procure a certain system i, then the constraint $u_i = 1$ is included in the formulation. If two systems are related in their procurement such that system 2 is procured only if system 1 is procured, a constraint of form $u_1 - u_2 = 0$ would be included. These decision constraints added flexibility to the model and allowed the evaluation of previously made or contemplated decisions regarding force effectiveness and opportunity costs with respect to the procurement of other systems.

The formulation of the mathematical programming model is expressed as follows:

$$\begin{aligned}
&\text{Max} \sum_{i=1}^{m} \sum_{j \in J_i} v_{ij} x_{ij} \\
&\text{s.t.} \quad \sum_{i=1}^{m} (\bar{c}_{ij} x_{ij} + \hat{c}_{ij} u_i) \le B_j; \;\; j = 1,\ldots,n; \\
&\qquad P_{min_{ij}} u_i \le x_{ij} \le P_{max_{ij}} u_i; \; i = 1,\ldots, m; \; j \in J_i; \\
&\qquad R_{min_i} u_i \le \sum_{j \in J_i} x_{ij} \le R_{max_i}; \;\; i = 1,\ldots, m; \\
&\qquad (1 - p_i) x_{ij-1} \le x_{ij} \le (1 + p_i) x_{ij-1}; \;\; i = 1,\ldots, m; \; j \in J_i; \; (j-1) \in J_i; \\
&\qquad d_k \le f_k(\mathbf{u}) \le D_k; \; k = 1,\ldots,K; \\
&\qquad x_{ij} \ge 0; \;\; i = 1,\ldots, m; \; j \in J_i; \\
&\qquad u_i \in \{0,1\}, \;\; i = 1,\ldots, m.
\end{aligned}$$

where

$n =$ number of years in the planning horizon,

$J_i = \{j : \text{system } i \text{ can be procured in year } j,\ j \in \{1,\ldots, n\}\}$,

$m =$ number of candidate procurement programs,

$x_{ij} =$ quantity of system i produced in year j,

$v_{ij} =$ system effectiveness coefficient of system i for year j,

$\bar{c}_{ij} =$ unit variable cost of system i in year j,

$\hat{c}_{ij} =$ fixed cost of system i in year j,

$B_j =$ RDA funds available in year j,

$P_{min_{ij}} =$ minimum allowable production quantity of system i in year j,

$P_{max_{ij}} =$ maximum allowable production quantity of system i in year j,

$R_{min_i} =$ minimum quantity of system i required by the target force structure,

$R_{max_i} =$ maximum quantity of system i required by the target force structure,

$p_i =$ allowable percentage deviation from previous year production quantity,

$d_k =$ minimum value for decision constraint k,

$K =$ number of decision constraints,

$D_k =$ maximum value for decision constraint k,

$f_k(\mathbf{u}) =$ decision constraint function of the vector of u_i variables.

Another use for binary variables, not shown above, arose from the requirement to include the nonlinear learning curve costs in the optimization, as described in the section above on cost analysis. A piecewise linear approximation was used to represent these costs, precipitating the need for another class of binary variables. The development of this approximation is discussed in detail by Loerch [14].

This model was implemented using the Optimization Subroutine Library (OSL), on an IBM RISC 6000 work station. A matrix generator was written in FORTRAN. The mixed integer program had approximately 4,000 rows with 3,000 variables, of which about 800 were binary integers, and 5,500 non zero elements. The run time for this model was between 10 and 60 minutes of CPU time on the IBM RISC 6000 590, with an average of 20 minutes.

The model was successfully used to assist the Army Staff in evaluating the various alternative weapon system mixes considered for procurement. The model was particularly useful in identifying the years in which budget constraints were extremely tight with respect to planned production campaigns, suggesting modifications that could be made to the proposed programs. The model was also useful in identifying systems that were excluded from the solution when other systems, or combination of systems, were forced to be procured. This capability gave the Army leadership a window into the cost of their decisions as they related to system tradeoffs.

The use of the optimization model for the purpose of comparing alternative strategies and evaluating tradeoffs far outweighed the fact that a particular recommended system mix was produced. The feedback we received from decision makers indicated that these insights were much more useful

in the decision making process than specific recommendation since they tended to be more globally applicable and because the situation with respect to decisions that were made and funding levels was constantly changing. For this reason, the use of this optimization model was iterative, as more and more "What-if" questions were asked.

9. THEATER FORCE EVALUATION

The need arose to have the capability to evaluate the acquisition strategy recommendation made using the optimization module in the context of theater operations and over various force structures.

The previously described modules in the methodology dealt solely with effectiveness of modernization systems in the context of the operations of a fully modernized Army corps. The force structure of the entire Army was given and assumed fixed. For example, a 12 division "Base Force" was assumed during the conduct of the study and the quantity required to be procured for each modernization system was specified by the sponsor as a function of that force.

As the budget building process progressed, however, consideration was given to the reduction of the base force to less than 12 divisions. The question then needed to be answered as to the capabilities of the reduced force when some of the monetary savings achieved from the force reduction are applied to increased modernization. This question can only be answered by analyzing the force at the theater level.

The procedure was simple. A system mix and acquisition strategy was developed using the optimization module, with the budgetary constraint relaxed to take into account the additional funds made available through the reduction in force, and with the required quantities of equipment changed to reflect the reduced force structure. The equipment recommended for procurement was then distributed to the units in the designated force, and this force was simulated in an agreed upon scenario. The results were then compared to those from the original base force.

The methodology was limited in the sense that the theater simulation was much more aggregate, so some of the systems whose contribution could be measured at the corps level had no measurable effect at the theater level. Also, the procedure was fairly manpower intensive, so only a few alternative force structures could be evaluated within the required time frame.

Nevertheless, the results proved interesting and insightful, and this part of the methodology was made a permanent part of the VAA methodological framework.

10. RESULTS

Figures 3 and 4 provide an example of analysis output provided to senior Army decision makers. Figure 3 is a so called "X chart" which shows which candidate programs were recommended for procurement and which ones were not. Systems are categorized and listed in order of Battlefield Operating System, namely Air Defense (AD), Aviation (AVN), Command and Control (C2), Engineer (ENGR), Indirect Fire (IDF), Intelligence and Electronic Warfare (IEW), Logistics (LOG), and Maneuver (MVR). An X in the chart indicates that the particular system was recommended in the optimization module for a particular excursion and a blank

indicates that it was not. Typically, several excursions were performed in each analysis. Each excursion examined a different set of conditions. These conditions included the level of funding for RDA programs and different decisions that had been made or were contemplated regarding the various candidate programs. The tradeoffs associated with each mix may be seen by comparing across the columns and identifying those systems which come into and leave the recommended list as the conditions change. We note that the typical set of solutions will be characterized by several systems that are always in the recommended list, several that are never recommended, and still others that are sometimes in and sometimes out of the recommended list. Thus the decision makers can assess the relative desirability of the various programs under a given set of conditions.

Figure 4 provides an example of graphical displays of the combat effectiveness of the various mixes of systems recommended. These estimates are made using the response surface models developed in the Combat Effectiveness module. Ideally, the combat simulation would be re-run with the various mixes portrayed explicitly. However, the results of these analyses were usually needed within a 24-48 hour period, making it impossible to re-run the combat simulations. As such, the response surface model became an important tool for performing quick response analyses. This output is extremely important for the evaluation of the recommended system mixes because it shows the effectiveness of the force in terms that the decision maker can understand. We have found that reporting differences in the objective for various excursions is not meaningful. The individual measures that are used to build the objective function must be broken out and shown separately. Similar displays are produced for all the individual measures.

Typically, no one recommended system list from the excursions dominates the others in all measurement criteria. Such is the case in figure 4 which shows the fractional exchange ratio. Insight can be drawn, however, from the examination of the recommended systems and their performance in various scenarios. Note also that the results of a base case run in which no modernization is portrayed is also shown. This run is used to show the contribution of the modernization program as a whole.

Not shown here, but provided to the decision makers for each excursion, is a table showing the yearly procurement quantities as well as a breakdown of the research, development, test and evaluation costs, the fixed production costs, and the variable production costs for the systems on the recommended procurement list.

	Recommended VAA Systems						
	VAA Systems By BOS		Exc 1	Exc 2	Exc 3	Exc 4	Exc 5
AD	AD Veh	Air Defense Vehicle	X	X	X	X	X
	MSL 1	Air Defense Missile 1	X	X	X	X	X
	Radar 1	Air Defense Radar 1	X	X	X	X	X
	Radar 2	Air Defense Radar 2	X		X	X	X
	MSL 2	Air Defense Missile 2	X	X	X	X	X
AVN	Helo 1	Helicopter Upgrade 1			X		
	Helo 2	Helicopter Upgrade 2			X		
	Helo 3	New Helicopter 3	X	X	X	X	X
	Helo 4	New Helicopter 4		X			X
C2	CC 1	Command and Control System 1	X	X	X	X	X
	CC 2	Command and Control System 2	X	X	X	X	X
	CC 3	Command and Control System 3	X			X	
	CC 4	Command and Control System 4	X	X	X	X	X
	CC 5	Command and Control System 5	X	X	X	X	X
	CC 6	Command and Control System 6	X	X	X	X	X
ENGR	Eng 1	Engineer Equipment 1	X	X	X	X	X
	Eng Veh	Engineer Vehicle	X	X	X	X	X
	Mine 1	Mine System 1	X	X	X	X	X
	Mine 2	Mine System 2	X	X	X	X	X
	Mine 3	Mine System 3	X	X	X	X	X
IDF	Ammo 1	Artillery Ammunition 1	X	X	X	X	X
	Arty 1	Field Artillery System 1	X		X	X	
	Radar 3	Artillery Radar System 3	X	X	X	X	X
	Radar 4	Artillery Radar System 4	X	X	X	X	X
	MSL 3	Artillery Missile System 3		X			X
	MSL 4	Artillery Missile System 4	X		X	X	X
	Arty Veh 1	Field Artillery Vehicle 1	X	X	X	X	X
	Arty Veh 2	Field Artillery Vehicle 2	X		X	X	
	Ammo 2	Artillery Ammunition 2	X		X	X	
IEW	Sensor 1	Intelligence and Electronic Warfare Sensor 1	X	X	X	X	X
	Sensor 2	Intelligence and Electronic Warfare Sensor 2	X	X	X	X	X
	Radar 5	Intelligence and Electronic Warfare Radar 5	X	X	X	X	X
	IEW 1	Intelligence and Electronic Warfare System 1	X	X	X	X	X
	IEW 2	Intelligence and Electronic Warfare System 2	X	X	X	X	X
LOG	Log Veh 1	Logistics Vehicle 1	X	X	X	X	X
	Truck 1	Tactical Vehicle 1	X	X	X	X	X
	Truck 2	Tactical Vehicle 2	X	X	X	X	X
	Log Veh 2	Logistics Vehicle 2	X	X	X	X	X
MVR	Armor 1	Armored Vehicle 1	X	X			
	MVR Sys 1	Maneuver System Upgrade 1	X	X	X	X	
	MSL 3	Anti-Armor Missile System 3	X	X	X	X	X
	Armor 2	Armor System Upgrade 2				X	
	Armor 3	Armor System Upgrade 3	X			X	
	Ammo 3	Armor System Ammunition 3	X	X	X	X	X
	Ammo 4	Armor System Ammunition 4	X	X	X	X	X

Figure 3. X-Chart - Recommended Systems Lists by Excursion

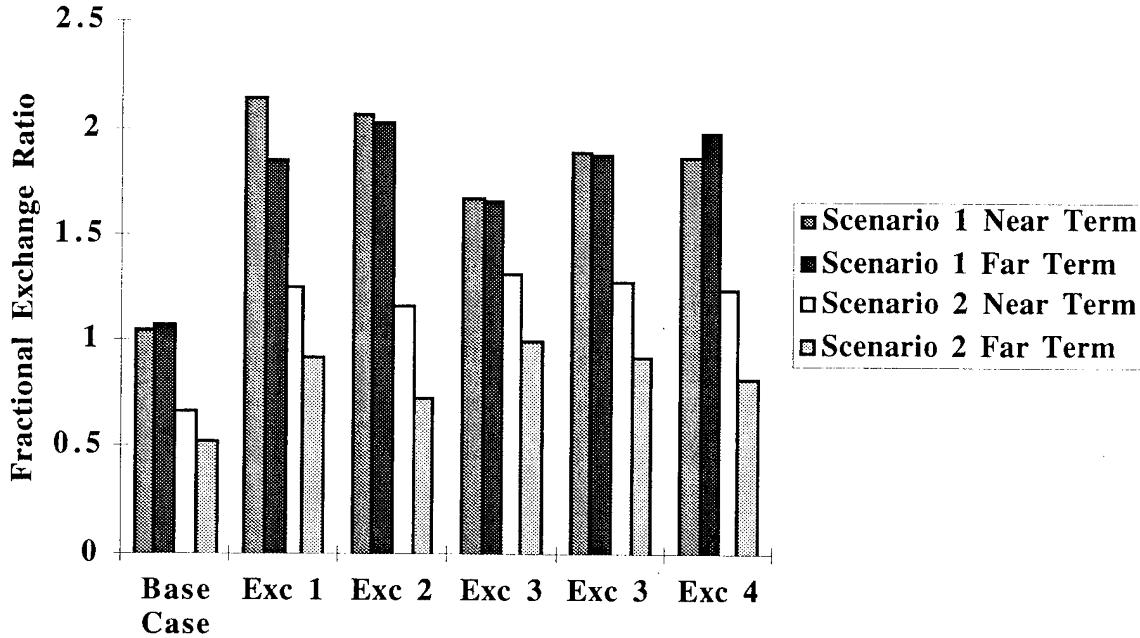

Figure 4. Combat Performance of Recommended System Mix

11. SUMMARY AND CONCLUSIONS

The primary result of the development portion of the study was the definition of a flexible and rational methodology to support the POM process and Army program development. The methodology developed during this effort provided a way of capturing the subjective elements used by decision makers in conducting tradeoffs between alternatives through the use of judgment weights. This phase of the study also provided some important insights into the use of aggregated effectiveness models, new costing approaches, and optimization techniques which were built upon later.

As the VAA methodology was used to support decision making, the following observations were made.

(1) Each module of the methodology provides important information and insight to the decision makers. For example, the response surface methodology provided important insights into contribution of different weapons systems to the performance of the force in combat.

(2) The data collection effort and subsequent building of the VAA databases resulted in a comprehensive set of data that was not available elsewhere.

(3) The purpose of VAA is to build the capability to do quick turnaround "What If" analyses. To meet this goal, however, requires eight months or more of preliminary effort. Once this preliminary work is completed, new solutions based on the questions and constraints imposed by the decision makers can be computed very rapidly.

The use of Value Added Analysis provides decision makers at the Department of the Army level with a tool to quickly evaluate programming and budgeting decisions in the area of equipment modernization. Additional work is needed to expand the methodology to include

expenditures in other areas such as force structure, operations and training, personnel, and facilities.

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